Beyond Power over Ethernet: the development of Digital Energy Networks for Buildings

James Johnston
Arup and BRE PhD Student, Mechanical Engineering, University of Strathclyde
james.r.johnston@strath.ac.uk

Prof John Counsell
BRE Centre of Excellence, Mechanical Engineering, University of Strathclyde
john.counsell@strath.ac.uk

Garry Banks
Director, Arup Liverpool
garry.banks@arup.com

Dr Matt Stewart
BRE Centre of Excellence, Mechanical Engineering, University of Strathclyde
matt.stewart@strath.ac.uk

Abstract

Alternating current power distribution using analogue control and safety devices has been the dominant process of power distribution within our buildings since the electricity industry began in the late 19th century. However, with advances in digital technology, the seeds of change have been growing over the last decade. Now, with the simultaneous dramatic fall in power requirements of digital devices and corresponding rise in capability of Power over Ethernet, an entire desktop environment can be powered by a single direct current (dc) Ethernet cable.

Going beyond this, it will soon be possible to power entire office buildings using dc networks. This means the logic of "one-size fits all" from the existing ac system is no longer relevant and instead there is an opportunity to redesign the power topology to be appropriate for different applications, devices and end-users throughout the building.

This paper proposes a 3-tier classification system for the topology of direct current microgrids in commercial buildings – called a Digital Energy Network or DEN. The first tier is power distribution at a full building level (otherwise known as the microgrid); the second tier is power distribution at a room level (the nanogrid); and the third tier is power distribution at a desktop or appliance level (the picogrid). An important aspect of this classification system is how the design focus changes for each grid. For example; a key driver of the picogrid is the usability of the network – high data rates, and low power requirements; however, in the microgrid, the main driver is high power and efficiency at low cost.

Keywords Direct current, Digital, Power over Ethernet, Dc microgrid, DEN

1.0 Introduction

This paper will highlight some of the key challenges that the electric power network in commercial buildings faces for the 21st century. Many of the challenges are a result of the rapid changes in society in the last few decades and those that are predicted in the next. Transforming the legacy power network to meet these challenges will be difficult, as an entire eco-system, built up over the last 100 years now depends on it.

Before discussing how this legacy system could evolve, it is necessary to set out the context of what actually influences the design of a power network. The power network is part of a larger system – which at the highest level can be split into three components – the power supply (input), the power network (process) and the applications (output).

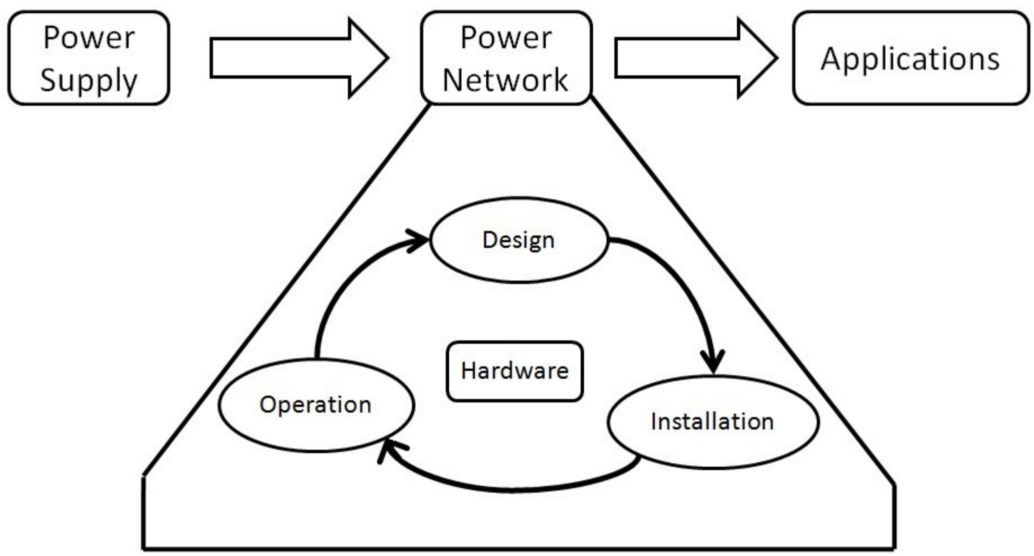


Figure 1: The Electric Power System Context

Taking a systems approach to design, it is clear that the topology of the power network is dependent on the context of its inputs and outputs. As seen in **Figure 1**, this does not just refer to hardware, but the holistic interaction between design, installation and operation. First of all, this paper will focus on the inputs: the context from the power supply.

1.1 AC: Context from the Power Supply

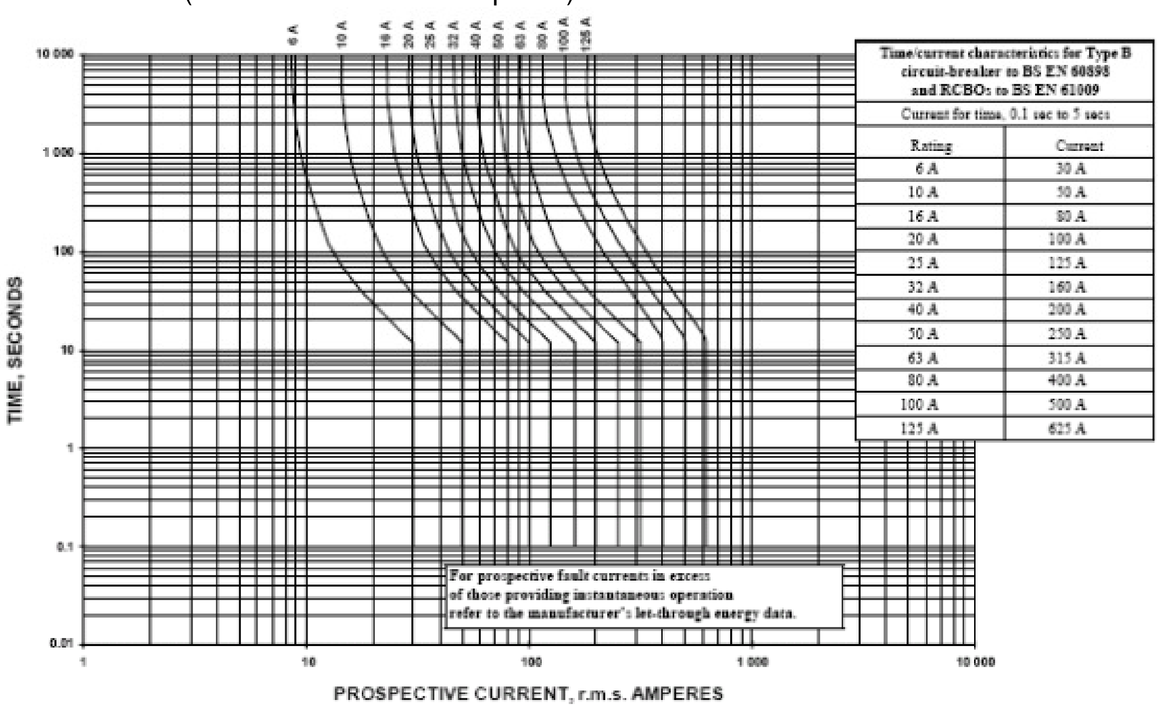
The most defining aspect of the existing power supply is that it comes from a nationwide grid of interconnected power stations. The benefit for centralised generation and control of power is that at a strategic level the variation in demand is far smoother and predictable than on a local or individual building level and hence it is easier to match with scheduled supply.

In the UK, there is an open market for trading power generation and demand contracts, which can be secured at any time between 7 years and 30 minutes before, and can predict demand incredibly accurately depending on the time of the year and weather forecast. The remaining fine tuning is done automatically by the synchronous generators themselves, which can vary their fuel input depending on the frequency signature of the grid [1]. This “power station” centric power supply context very much shapes the way in which power networks are designed in buildings: as they are seen as end-users rather than participants in the process. Three core examples are listed below (not an exhaustive list).

Firstly, as voltage stability is controlled by the national grid, the building only has to ensure that cables are sized not to reduce the voltage level beyond a certain level. IET Wiring Regulations BS 7671:2008 recommends a maximum voltage drop of 3% for lighting and 5% for small power (for a DNO supply) [2].

Secondly, as the power supply is not actively controlled by the building – and in a sense is always live, there are requirements for isolation devices to be installed throughout the different networks in the building, so that maintenance can be performed.

Finally, relative to the size of the building, the national grid power supply can provide an infinite amount of current, if requested. This means that protective measures are required to be in place to cut the supply if a fault condition, such as a short circuit or earth fault is created. The wiring regulations set out maximum disconnection times under different circumstances [**Figure 2**]; which aid the designer in selecting adequate cabling, specifying the protection devices and aligning them to achieve discrimination (downstream circuits trip first).



Time/current characteristics for Type B circuit-breaker to BS EN 60898 and RCBOs to BS EN 61009	
Current for time, 0.1 sec to 5 secs	
Rating	Current
6 A	30 A
10 A	50 A
16 A	80 A
20 A	100 A
25 A	125 A
32 A	160 A
40 A	200 A
50 A	250 A
63 A	315 A
80 A	400 A
100 A	500 A
125 A	625 A

Figure 2: Type B Circuit Breaker: Automatic Disconnection and Discrimination (taken from BS7671:2008 [2])

Like the design process, the plethora of devices required to implement an electrical installation are mostly legacy devices, and many date back to the start of the electricity industry. Indeed the isolation switch, the electric meter and the fuse were patented by Edison in 1869, 1881 and 1890 respectively and in many respects have not changed significantly [3].

One of the most common protection devices in buildings – the circuit breaker (see **Figure 3**) – is in most situations still a mechanically operated device. Like the fuse, the circuit is broken using the immense power of the fault condition itself, rather than using smarter solutions provided by digital monitoring and control.

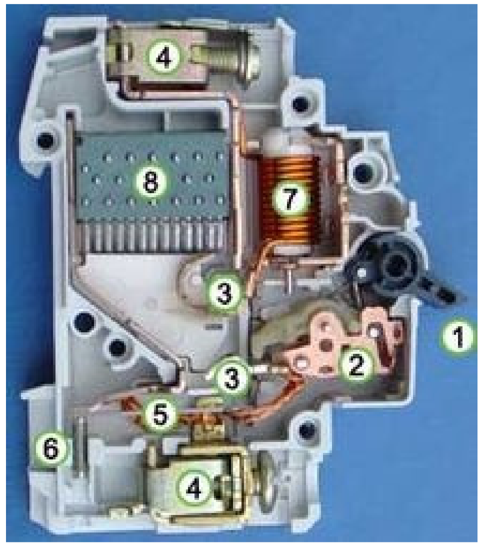


Figure 3: Insides of a mechanically operated circuit breaker [4]

1.2 Context from the Applications

Just as the core design methodologies and hardware requirements in the wiring regulations can be derived from the centralised power generation topology, other key aspects such as the voltage levels have also been optimized for legacy applications that date right back to the start of the industry.

Building on work undertaken by Thomas Swan, Edison in 1880 filed a patent for “System of Electric Lighting”. His system generated 110V dc to be used by carbon filament lamps. Thinking holistically, Edison realised that a higher voltage would reduce the current and hence could use less copper in transmission. However, his aim was to provide a system that could be competitive to the ubiquitous gas lighting network. As those early carbon filament lamps were very sensitive to voltage levels, Edison chose 110V as a compromise between minimising distribution costs and maximising lamp lifespan.

By 1899 developments in lighting technology had made metal filaments available. Berliner Elektrizitäts-Werke (BEW), a German utility company realised that they could double this voltage to 220V, and hence radically reduce both the current and the amount of copper used in transmission. These savings were offset against the expense of changing consumer appliances and motors. This eventually became the standard topology for electricity use throughout Europe; but the US, perhaps with its head start in the industry could not find the business case to change [5].

Many core aspects of the electricity supply in our buildings can similarly be traced back to these early routes. And although over the years they have incrementally developed: increasing efficiency and cost effectiveness, fundamentally they have not changed. As described by Morton, after the standardisation of the industry in the early 20th century, the locus of innovation had shifted, from the delivery of electricity to its applications [6]. However, we are now reaching a tipping point where so many of the key contextual parameters are so far away from optimal, that for the first time in over 100 years there is a clear opportunity for change.

2.0 Drivers of Change

There are two areas of change which are putting into question the logic of this centralised ac system:

- The rise of digital technology as a key application in our buildings
- The rise of distributed generation as a key power supply to our buildings

2.1 Digital Technology

As was elaborated in a previous study by the author [7], there could be four major revolutions that will have a significant impact on the power demand in our offices:

- **Generation-Y:** increased mobility is changing the role of the office; from being a fixed place for private work, to a hub for meeting people and collaborating.
- **Ubiquitous Computing:** the ability to access data ubiquitously is driving the need for virtual desktop hubs and ever more mobile ICT.
- **Solid-state lighting**: LEDs are set to revolutionize the lighting market with commercially available space lighting to reach 188lumens/Watt by 2015.
- **Surface Computing:** this describes the evolution of monitors into full surfaces for visual and touch interaction. In the next few years OLED screens are expected to make a big impact in commercial offices and E-Paper could eventually make printers and paper redundant.

In general the trends suggest ever increasing numbers of digital devices; each with ever reducing power demands (although it is unclear whether overall power could reduce). Some key problems that the 230V alternating current power supply creates are outlined in the following paragraphs.

Unfit for purpose: by 2015, literally every single desktop device in the office space could run on low voltage direct current (LVDC) and consume between 0.5 and 30W. See Table 1 for a selection of commercially available (as of end of 2011) low power devices [8].

Device Type	Brand	Features	Operational Power
Smartphone	HTC (Q1 2012)	1.5GHz Quad Core	2.5W
Tablet	ASUS	Keyboard Dock	5W (15W peak)
Tablet	Lenovo	Keyb. & dock, Win7	8W (25W peak)
Laptop	Samsung	i3 dual core	20W (65W peak)
Laptop	Apple	A4 CPU	17W (50W peak)
Notebook	Sony	i3 dual core	17W (45W peak)
Light PC	CompuLab	1.6GHz Dual Core,SSD	10W
Thin Client	HP	1.2GHz Dual core	15W
Monitor	BenQ	19” WXGA LED/LCD	12W
Monitor	Samsung	22” Full HD, LED/LCD	22W

Table 1: Operational power demand of commercial ICT devices – CNET [8]

Extrapolating into the future, it appears likely that power demand will continue to drop, according to Koomey’s Law. As Koomey discovered in 2009, the electrical efficiency of computing (the number of computations that can be completed per kWh of electricity) since the start of personal computing has doubled every 18 months (see **Figure 4**) [9].

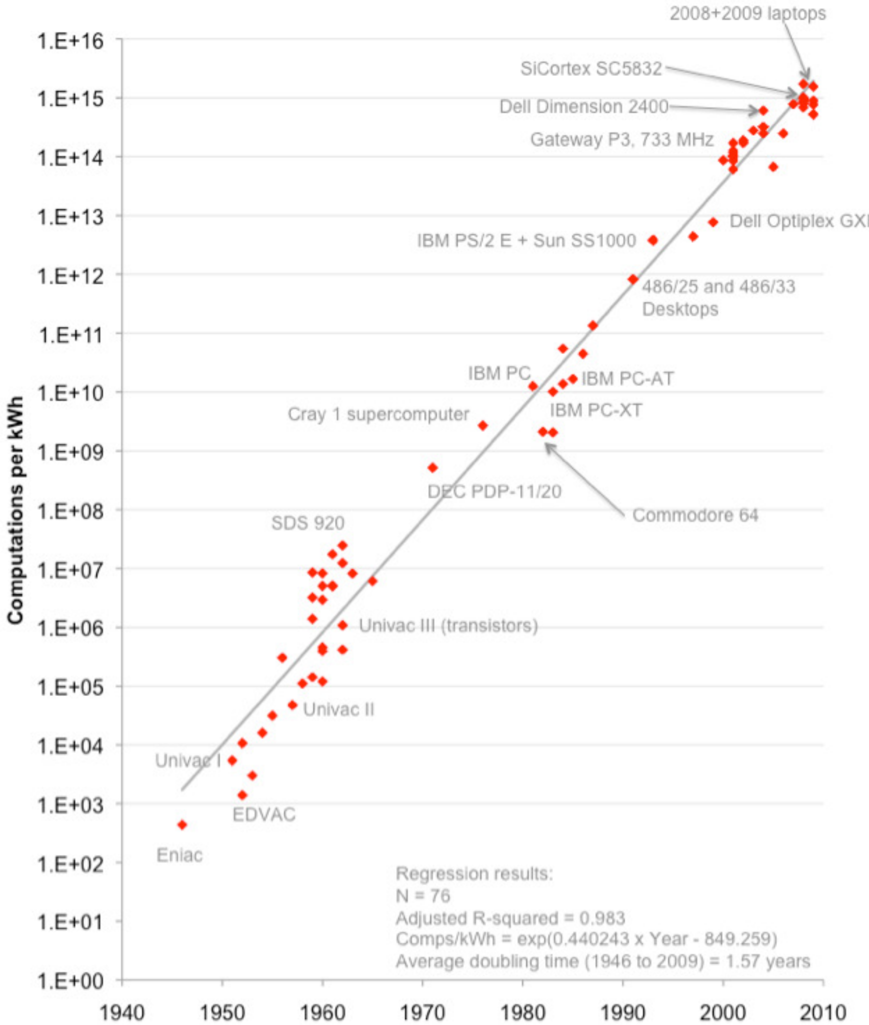


Figure 4: Koomey's Law – Efficiency of ICT doubles every 18 months [9]

Despite this dizzying progress, users are still given a 230V ac supply designed to deliver 3000W (13Amp plug). This not only means that the cables are oversized and therefore expensive; but the insulators and plugs have to be onerously designed (and require regular PAT testing) to mitigate the risk of electric shock.

Ac/dc rectifiers: perhaps the most obvious problem is in the number of power supply units (which are required to rectify the alternating current to direct current). Requiring ac/dc rectifiers for every device adds expense and inefficiency, and the extra components reduce the overall mean-time-to-failure (MTTF) [10].

Due to the non-linear nature of the current and voltage requirements of ac/dc rectifiers, multiple rectifiers can cause havoc with the power factor of the ac mains (relationship between current and voltage phases). These can create harmonics which can cause stress on neutral return cables and transformers and requires power factor correction to be installed at the main incoming supply point; adding even more cost and inefficiencies [11].

Finally, with the increasing number of rectifiers connected to final circuits, it becomes ever more difficult for residual current devices (RCDs) to be sized correctly to pick up on real problems, whilst ignoring the leakage currents of low quality power supply units (PSUs) [12].

Resilience: an important aspect of modern digital technology is the requirement of uninterruptable power. Unlike traditional loads such as lighting, ICT deals with data, which can be lost or destroyed if not shutdown properly. Uninterruptible power supplies (UPS) are battery systems which are designed to synchronise with the ac grid, and provide local power in the event of grid failure. The requirement of multiple conversions: from ac to dc (to charge the battery), back to ac (to supply local power), only to be used natively in dc for ICT devices is an inefficient and costly system.

2.2 Distributed Generation

The second driver of change is distributed generation. It is expected that buildings will always need a baseload of power from centralised production; but looking to the future, analysts predict there will be a much larger share of energy which is sourced and controlled locally [13].

- **CHP** – utilising the waste heat from local power generation increases roundtrip efficiencies. Looking to the future, there is much interest in the role of Fuel Cells in providing CHP capability: with their higher efficiencies and no moving parts. The US DoE predicts that Fuel Cells will revolutionise distributed generation if the high manufacturing costs can be tackled [14].

- **Solar Photovoltaics** – in the last 5 years the global solar industry has really kick started. With the feed-in tariffs in the UK, many homes and offices can afford solar PV on their roofs. However, crystalline-Si PV modules only represent 1st generation technology. In the next few years, it is expected there will be rapid increase in the production of 2nd generation Thin Film technology; which will revolutionise the way PV will interact with our buildings, such as transparent coatings on windows [15].

The European Photovoltaic Industry Association has predicted that PV will reach grid parity in as little as 2 years in Italy and 8 years in the UK [16]. Looking at long term trends, the International Energy Agency in 2011 suggested that the majority of the world's electricity supply could come from solar in as little as 50 years [17]. These predictions herald massive changes in the traditional idea that buildings are end-nodes on a centralised ac grid. The following paragraphs outline some specific problems about the incompatibility of distributed generation with the "power-station centric" grid.

Inverters: Fuel Cells and PV both naturally produce direct current. Today, they need to go through an inverter to convert this into alternating current – and therefore synchronise with a national grid – only to be rectified back into dc and used locally by the dominant load in commercial buildings – digital technology. This strategy adds unnecessary components, inefficiencies, complexities and cost.

Unpredictable: Solar PV is seen as a problem by utilities because it is out of their control, hence making their supply/demand matching exercise more difficult, and can require them to reinforce local substations against high negative power flow. (Small scale consumers are therefore only paid a fraction of the price they buy at (3p/kWh)). However, the complexities of creating hybrid autonomous/grid-connected systems;

with the onerous islanding, isolation and synchronisation requirements, and hence the extra cost, efficiency and functionality barriers; means it is rarely adopted [18].

2.3 Summary

Table 2 outlines a summary of the expected technologies to be found in an office from 2015 (note: does not include office kitchen devices).

Load	Alternating or direct current?
PCs	Direct current
Virtual Terminals	Direct current
Laptop/Notebook	Direct current
Tablet/Smartphone	Direct current
E-Paper	Direct current
Server Rooms	Direct current
LED lighting	Direct current
OLED lighting/Monitor	Direct current
Small Motors (DC Fan Coil Units)	Direct current
Large Motors	Variable alternating current*
PV (Crystalline Si & Thin Film)	Direct current
Fuel Cells	Direct current
Battery Cells	Direct current
** It is interesting to note that the only devices which naturally use alternating current are large synchronous motors. However, large motors are now mandated to include some level of speed control. Most use variable frequency drives (VFDs) which require the constant frequency ac to be rectified to a central dc bus before inverted at a varying frequency.*	

Table 2: Current characteristics of office loads of the future (2015)

We have a situation where almost all devices consume direct current, and far more of the power is going to be generated locally producing direct current. There is a clear opportunity to redesign the power network to a locally controlled and operated direct current microgrid. A study by Hammerstrom has suggested that a local dc network is the most efficient way to use power when there is a large influence from digital loads and distributed generation [19].

A locally controlled dc microgrid for the 21st century will be designed using a completely different set of contextual parameters than the legacy ac grid was at the end of the 19th century. A key difference is the opportunity that digital technology can offer, both in the design and operation of the microgrid.

To start the discussion on what the topology for a future dc microgrid should look like, the paper will now introduce the most successful digitally controlled dc microgrid solution which is ubiquitous in offices around the world: Power over Ethernet.

3.0 Seeds of Change – Power over Ethernet

3.1 History and Development

On May 22nd 1973 Bob Metcalfe faxed a memo to the team at Xerox's Palo Alto's HQ – and defined for the first time the "Ether network" [20]. It was "a broadcast computer communication, [...] specifically for in-building minicomputer communication". According to the memo, the usage of the word *ether* was to remove the focus from specific media types (i.e. cable) and instead focus on the network functionality. This attitude of having Ethernet (IEEE802.3 standard) as being distinct from the cable specifications (in ISO/IEC, EN and ANSI/TIA standards) still operates today.

In 2003, the Ethernet specification was developed to carry power alongside the data transmission. The IEEE802.3af Power over Ethernet (PoE) standard was produced specifying a maximum of 15.4-19.95W of power at 44-57V (direct current) down a single cable [21]. The initial driver for combined data and power was to service VoIP telephones. PoE was an elegant solution as it allowed ac/dc rectification to be done centrally; improving efficiency and cost-effectiveness, whilst achieving better resilience through the easy doubling up of power supplies (called N+1 protection) and easy connection of UPS systems.

In 2009, the PoE standard (IEEE802.3at) was further developed to increase power capability to 30-34.2W, and at the time perceived as a solution for larger security cameras and routers [22]. IEEE802.3at is backwards compatible with the earlier version of PoE (now called a Type 1 implementation) see **Table 3** for more details.

Like most aspects of the IT industry, PoE capability has not stood still since 2009. During 2011 Cisco, Microsemi and others have developed PoE systems which can deliver 60W per channel. Cisco teamed up with Samsung to deliver an integrated virtual desktop environment with a thin client and 22" monitor (see **Figure 5**) [23].

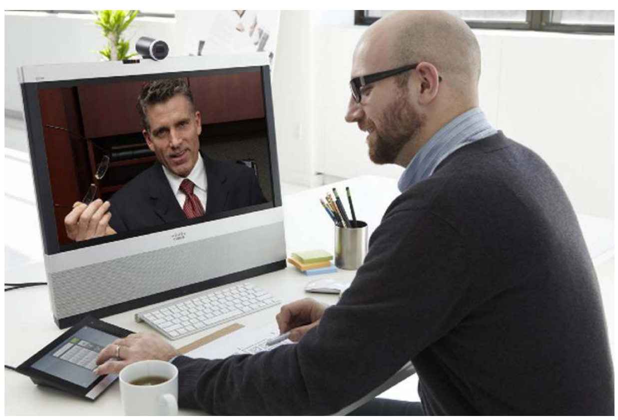


Figure 5: Commercially Available PoE Virtual Client System [23]

3.2 How does it work?

Power over Ethernet is a true smart power system, unlike mains ac power supply which is always available (and isolation is required when it is not wanted), the Power Sourcing Equipment (PSE) needs to talk to the Powered Device (PD) and power is only given when the right conditions are met. There is a PSE for each Ethernet port, (housed within the Switch or Midspan injector) and the PD is built into the end-device, or within an end terminal called a splitter. See **Figure 6** and **Figure 7** for the different switch and midspans topologies.

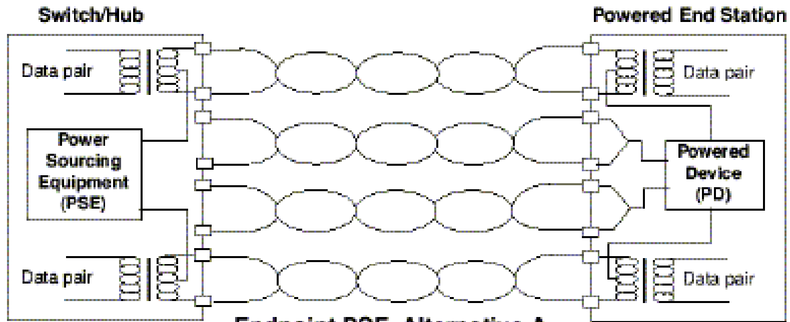


Figure 6: Endpoint PoE configuration with PSE injecting power onto data pair [22]

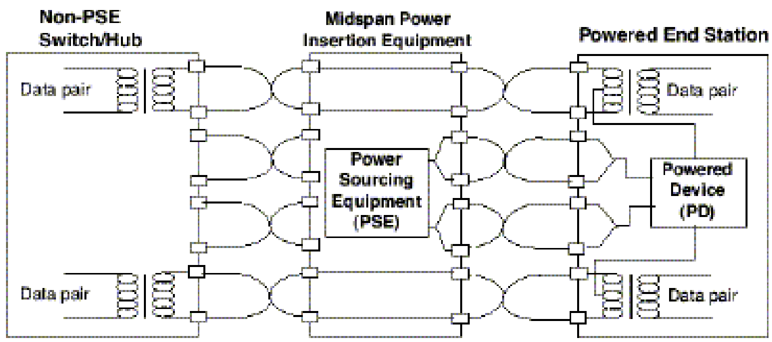


Figure 7: Midspan PoE configuration with PSE injecting power onto spare pair [22]

3.2.1 Digital Voltage Regulation

The voltage stability of the network is maintained within IEEE802.3at constraints by a Digital Power Supply connected to the PSEs. In a Type 2 system, the maximum voltage produced by the PSE is 57V and the minimum is 50V. This ensures that a minimum of 42.5V can be picked up by the PD, assuming an 7.5V loss over a 100m cable run [24]. In addition, far tighter voltage ripple and noise limits are set (maximum amplitude of 0.1V for 500kHz-1MHz ripple), in order for it not to interfere with the Ethernet data packet signals [22].

Type	Produced by PSE		Received by PD	
	Maximum Power	Voltage Range	Maximum Power	Voltage Range
1	15.4-19.95 W	44-57 V	12.95-19.95 W	37-57 V
2	30.0-34.2 W	50-57 V	25.5-34.2 W	42.5-57 V

Table 3: IEEE802.3at Max Power and Voltage Ranges [25]

3.2.2 Interfacing and Disconnection Processes

Before power can be sent down the cable, the PSE needs to talk with the PD to discover how much power it is asking for and to see if it passes the in-rush and under-voltage tests. (See **Figure 8**)

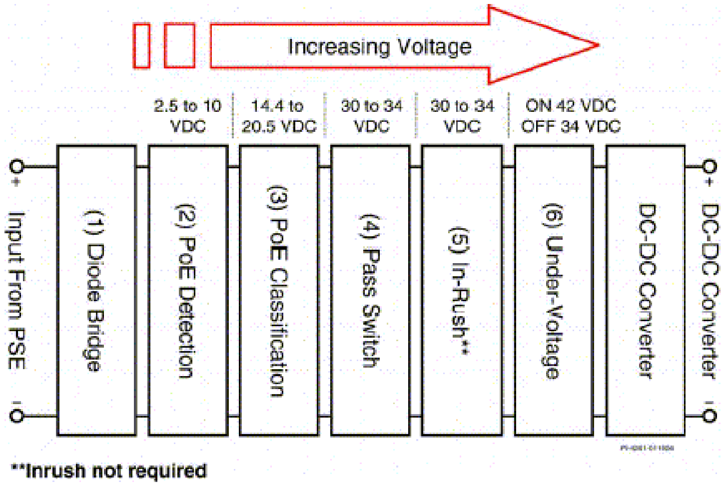


Figure 8: Sequencing diagram of a PD successfully interfacing with a PSE [24]

In the original PoE specification, the power requirements were done using hardware alone (resistance signatures), delivering 4 options as shown in **Table 4**:

Class	Min Power (W)	Max Power (W)
0	0.44	12.95
1	0.44	3.84
2	3.84	6.49
3	6.49	12.95
4	Reserved for IEEE802.3at	

Table 4: Resistance Signatures during PoE Classification

The maximum power levels are used to instruct the PSE whether a fault condition was occurring during operation. Using the same concept of disconnect times as with the ac system of circuit breakers/fuses (see **Figure 2**), the IEEE802.3af compliant devices conform to a similar chart of suitable current conditions, split into different categories of overload and short-circuits. (See **Figure 9**).

The key difference between the two strategies is in the method of disconnection. In the traditional ac system, the brute force of fault current is needed to trip the device, whilst in the dc system the PSE simply stops delivering power to the PD once the current characteristics fall outside requirements. This control is achieved digitally, using an IC within the PSE which samples the instantaneous current characteristics during operation.

The benefit of circuit breakers is that once they are tripped, they provide 100% isolation between supply and load through physical separation. Power over Ethernet gets around this problem using the concept of galvanic isolation, in which the high frequency transformer within the PD dc-dc converter does not allow any direct current flow when it is not being actively controlled [26].

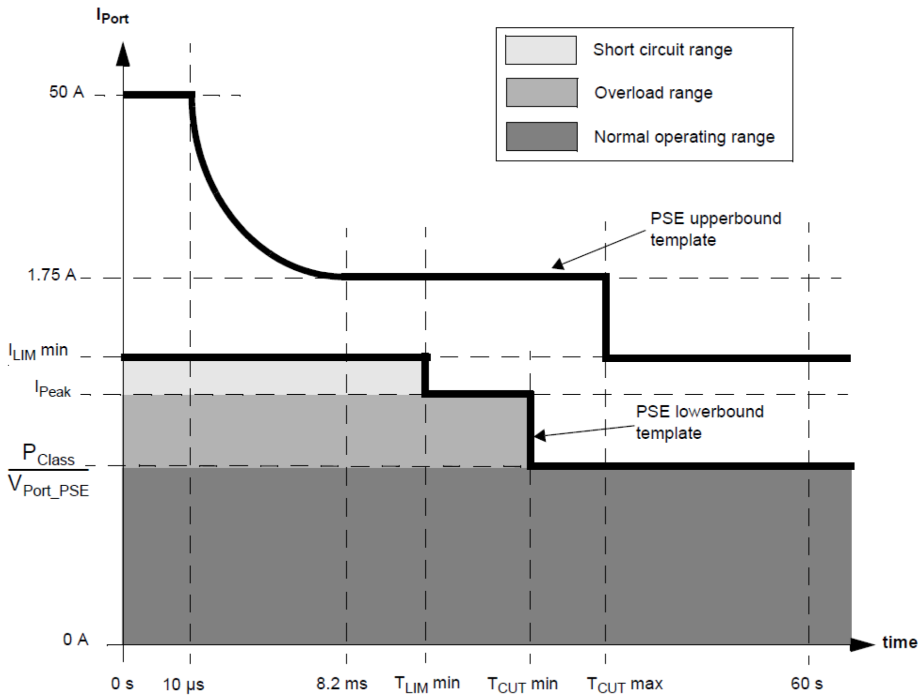


Figure 9: POWER_ON state PI operating current templates [22]

3.2.3 Control of 25W+ systems

A class 4 detection signal (See **Table 4**) means a Type 2 IEEE802.3at device is connected (up to 34.2W). This enables the use of dynamic power management, where communication between the PSE and PD is done using the data link (LLDP protocol). The main benefit of this is in allowing dynamic allocation of power from the PSU, which can then take advantage of the principle of diversity, creating smaller and more efficient PSUs.

The Cisco 60W UPoE solution claims to be IEEE802.3at compliant for detection, disconnect and voltage control. This means that at a functional and software level, there is no difference between the UPoE system and the IEEE802.3at systems.

3.3 Consumerisation of Power Networks

Power over Ethernet is more than just a novel solution for small power in offices. It could be said that aspects of the design locus are moving away from the building services engineer and into the realm of product manufacturers. This process of consumerisation of power networks can be seen in three distinct areas:

- **Voltage regulation**: with advances in digitally controlled power supplies and ever cheaper and powerful ICs, dc microgrids can easily mimic the stability of the national grid on a much smaller scale.
- **Protection**: dynamic power management and monitoring means that protection is inherently inbuilt into the dc microgrid – again IC solutions rather than mechanical brute force.
- **Cabling**: are also falling into the realm of consumer products. Manufacturers only develop cables of the categories defined by ISO/IEC, EN or ANSI/TIA standards (e.g. Cat 3, Cat 5e, Cat 7... etc) which are referenced by the IEEE.

As with everything else in the IT industry, the focus has moved to modular hardware solutions; serving as a platform for intelligent software solutions.

4.0 Beyond PoE – Digital Energy Networks for Entire Buildings

This paper has so far outlined the context in which power systems are designed and has introduced a comparison between the traditional centralised ac approach and the new digital and decentralised approach driven by the IT industry. Moving forwards, it is clear that whilst PoE is a good solution for small power loads, it is inadequate for plug-and-play connection of renewable energy (PoE only supports uni-directional power flow), and is not capable of higher power applications such as HVAC motors, server racks and office kitchens.

4.1 Topology Overview

The few academic studies into future dc microgrid topologies have generally constrained themselves by only investigating optimal voltage levels to maximise efficiency [10, 11]. Inherently these studies are very one-dimensional, as cost optimization is determined under very static assumptions and any indirect benefits are ignored. This is particularly significant with PoE, as a major benefit is the opportunity to share data and power over one cable.

Extrapolating on this, another important concept is the cost-saving potential from how suited the technology is for task. PoE uses <60V dc, a Safety-Extra-Low-Voltage (SELV), as it is designed for high interaction with humans. This relaxes specifications in the wiring regulations as it is inherently safe: and ultimately installation and repairs do not require a qualified electrician, saving on costs [27].

Other than PoE, there are three major new dc microgrid topologies that have emerged over the last few years.

4.1.1 24Vdc Ceiling Grid Topology for Lighting

The DC FlexZone Grid is a solution in which direct current power is sent down a ceiling tile grid at 24V, allowing individual luminaires to connect in a modular fashion.

Topology overview: a dedicated PSU (see in **Figure 10**, top right) supplies up to 100W at 24Vdc to each conductor embedded along the length of the ceiling tile grid structure (shown as the dotted blue line in the diagram). This PSU can be supplied using alternating current, or connect directly to solar PV to increase net efficiency [28].

As highlighted earlier, 24V dc would never be selected as a valid distribution topology in a purely academic study; due to the high losses or large conductor areas required. However, this is a clear example of how indirect benefits can dominate design: in this case the conductor has the dual job of transmitting power and adding to the structural integrity of the ceiling grid [29].

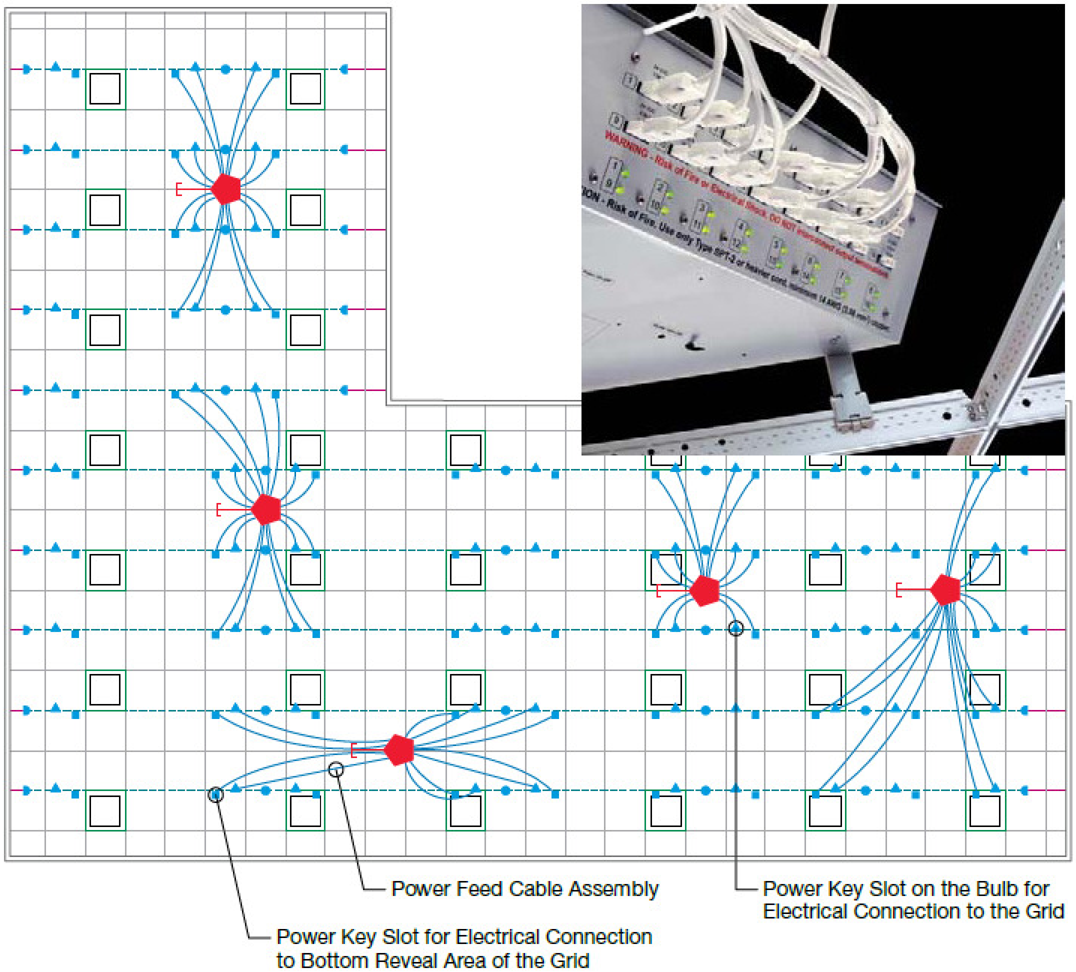


Figure 10: DC FlexZone Grid [29]

4.1.2 Variable voltage PoE topology for Lighting

Redwood Systems have developed a novel networked lighting solution, by adapting the existing PoE topology for LEDs [30]. However, PoE has been turned on its head, and instead of providing variable current at a constant 48V, it provides a variable voltage at constant current.

The reason for this is the different load characteristics of LEDs – which require a constant current input to operate. Hence, to mimic the same functionality as PoE, where all the drivers are located centrally – this current control would have to be done centrally too (see **Figure 11**).

The centralisation of drivers delivers similar benefits as PoE does for ICT (increased resilience and control, cheaper cabling and longer lasting end-devices). Furthermore, PoE-based systems are able to capitalise on the Ethernet standard for transmitting data. This means that not only can multiple sensors be connected to each outgoing port, but all this data can easily be connected to the internet and monitored remotely.

One potential disadvantage of a constant current system is having higher losses at part loading (as losses will be constant).

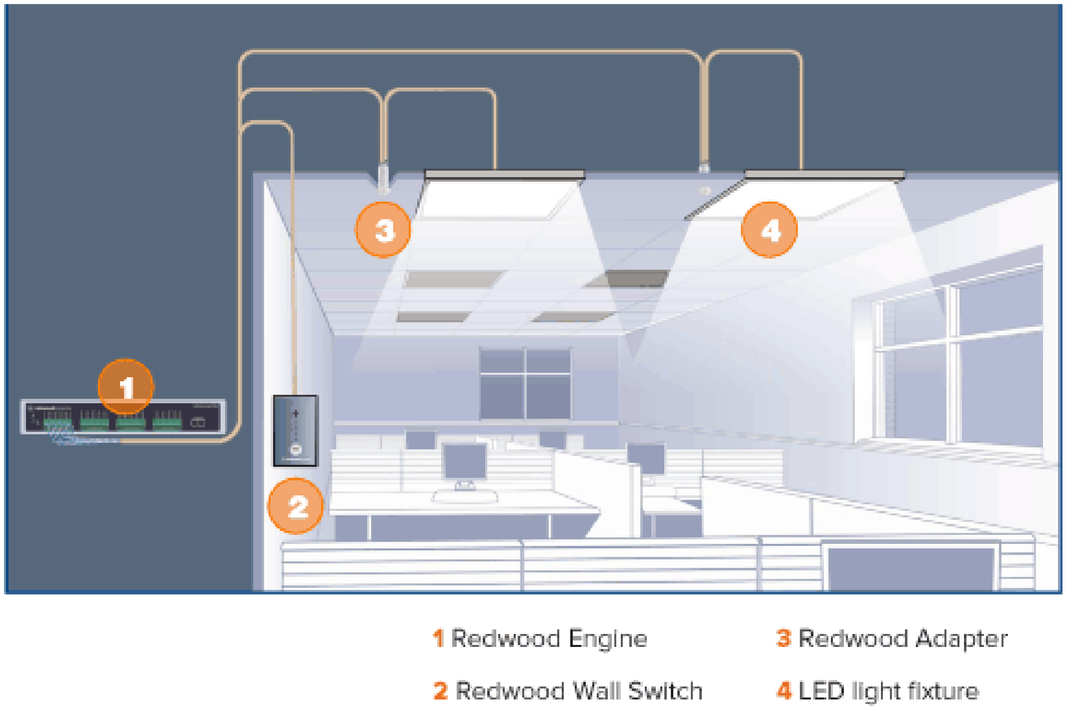


Figure 11: Variable Voltage PoE topology for Lighting [30]

4.2 380Vdc topology for data centres

The other major developments in dc microgrids have been for data centres. EPRI (Electric Power Research Institute) has developed a 380Vdc topology which can connect directly to server racks (See **Figure 12**). Benefits include higher reliability and efficiency (fewer conversions/points of failure), better power quality and easier connection of UPS systems and renewables [31]. Opponents cite that the benefits are too small to create a real business case for change, as most data centre equipment would need to be modified to accept a 380Vdc connection [32].

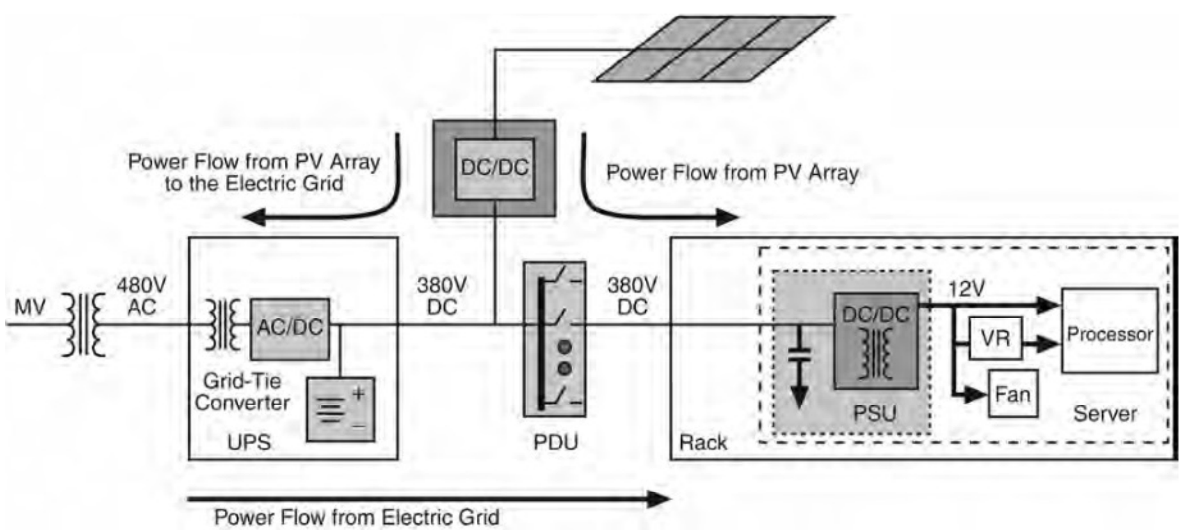


Figure 12: 380Vdc standard for Data centres

4.3 EMerge Alliance: DC Microgrid Standards

Understanding the importance of building a cross industry alliance, in 2009 the EMerge Alliance was created to develop standards for dc microgrids in buildings. Initially founded by the DC FlexZone Grid partners (Armstrong, NexTek et al); members and supporters have now grown to represent a significant number of leading technology companies, including GE, Phillips, Samsung, ABB and Intel [33].

In 2010, the EMerge Alliance incorporated EPRI's 380Vdc topology with their own 24Vdc topology to create a dual standard for occupied office spaces and data centres. Their occupied space standard focuses on the process of delivering a SELV 24V dc power capability to 4 separate areas of the room: the ceiling, walls, furniture and floors (see **Figure 13**) [34].

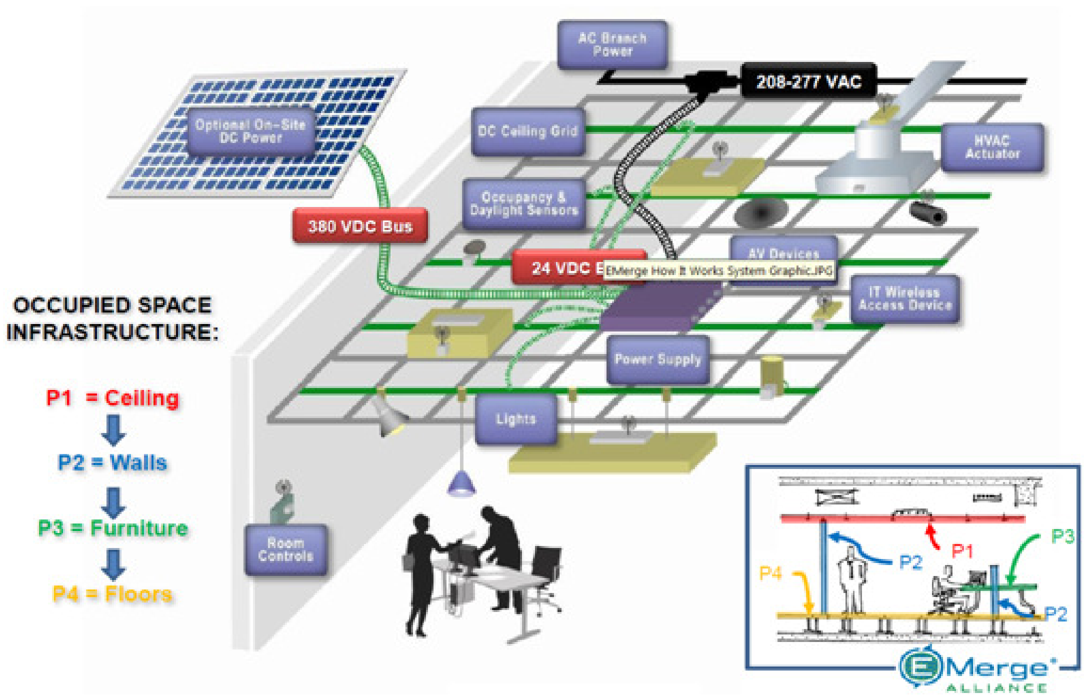


Figure 13: EMerge Alliance Occupied Space Standard [34]

The process of sending power down shared conductors represents a marked departure from the dedicated cable approach of PoE based solutions. Whether this signifies the start of a divergence between a dedicated and shared network for dc power, it is not clear at this early stage. What is evident is that the answer will not come from developments in the power systems alone, but alongside progress in data transmission technologies.

On one hand, it could be argued that through Koomey's law; the power demand will continue to decrease, whilst the data transmission requirements will increase. There could come a tipping point in the future, where it is not power but data bandwidth which limits the types of devices that can be connected by Ethernet.

On the other hand, there might not be such a drop in power. And more importantly, with the rate of innovation in data transmission technologies (especially with wireless and power line communication) – it is not obvious that Ethernet (and hence dedicated networks) will always be the best option for sending data packets.

5.0 Synthesis: Parallels between the Internet and Energy

Bob Metcalfe, inventor of Ethernet has defined a new concept: Enernet, which highlights the many parallels between internet and energy [35]. In a recent presentation, Metcalfe proposed that the fledging green energy industry could learn much from the progress and ultimate success of the internet in revolutionising communication [36].

The first lesson is that change will be gradual rather than sudden, and will take place over decades. The second lesson is that just like the internet, energy should be distributed and asynchronous from a central grid. Before the development of Ethernet, data packages would have to be synchronised to a central clock; which has intriguing parallels to today's problems with centralised synchronous ac power.

The final lesson is that the industry should be sub-divided into a series of frameworks and layers, similar to the TCP/IP models which outline the operation of the internet (see **Figure 14**, [37]). Each layer allows more focus for innovation, whilst retaining overall interoperability with its neighbouring layer. A key benefit of this approach is removing the complexity of connecting different network topologies together and hence increasing the functionality of the overall network [39].

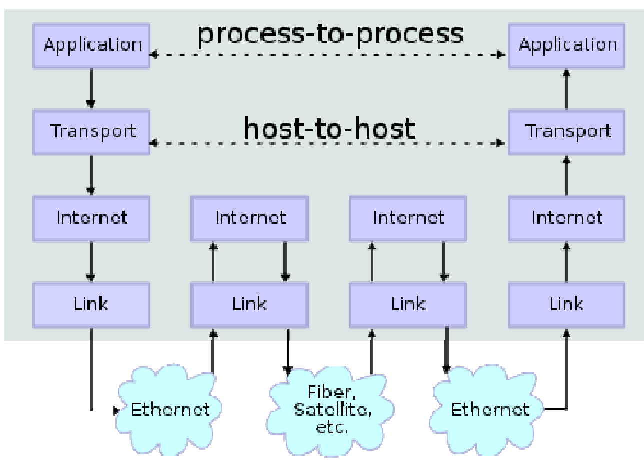


Figure 14: TCP/IP Model for Data Transmission [38]

5.1 The Digital Energy Network (DEN) Model

Progressing the ideas put forward by Metcalfe, a novel framework for distributed energy, called a Digital Energy Network, is proposed in this paper. Instead of outlining how packets of bits should be sent around a computer network, the focus has moved to the challenges of moving packets of energy. The first challenge is to develop a physical level classification system for network topologies; in computer science, this is analogous to classifying computer networks into wide area networks (WAN), local area networks (LAN) and personal area networks (PAN) etc.

Building on the evidence presented throughout the paper, it is proposed that the DENs physical level classification should be split into three categories; defined by the type of loads they supply and the level of interaction with occupants.

Microgrid: This is a building-wide distribution network serving higher powered loads/sources such as HVAC, Servers, large-scale roof PV and Fuel Systems (**Figure 15**). The focus for this grid will be on maximising performance and reducing losses. There will not be high data transmission requirements from these loads. As occupants will not generally be in direct contact with this network, a higher voltage (above SELV) is suitable. Commercial solutions which fit into this model are EPRI's 380Vdc solution for data centres.

Nanogrid: This is an occupied-zone distribution network, serving low power demands such as LED lighting, desktop hubs (PCs/thin clients etc), large screens, thin film PV on windows (see **Figure 15**). The focus on this microgrid is less on power transmission performance, and more on the overall benefits the network brings – such as flexibility, ability to send high levels of data, integration with furniture etc. To allow such innovations, clearly SELV voltages are a requirement. Commercial solutions which fit into this category are IEEE802.3af/at, Cisco UPoE, Redwood Systems and DC FlexZone Grid.

Picogrid: This a desktop level network, serving ultra-low power demands such as Smartphones, tablet PCs, sensor networks, energy harvesting devices and e-paper. Here the focus is on extremely high data transmission and hence power distribution is only seen as added value. Commercial solutions which fit into this category include USB 2.0/3.0 and Powermat (wireless charging) [40]. Finally: the end-appliance itself can also be defined as the picogrid power network.

The ability to remove the focus from particular hardware solutions allows for different technologies to evolve as necessary. By focusing on these three DENs topologies can allow a common ontology to be developed between the different grids, allowing higher layer applications such as advanced control of energy storage and distributed generation far greater scope for integration.

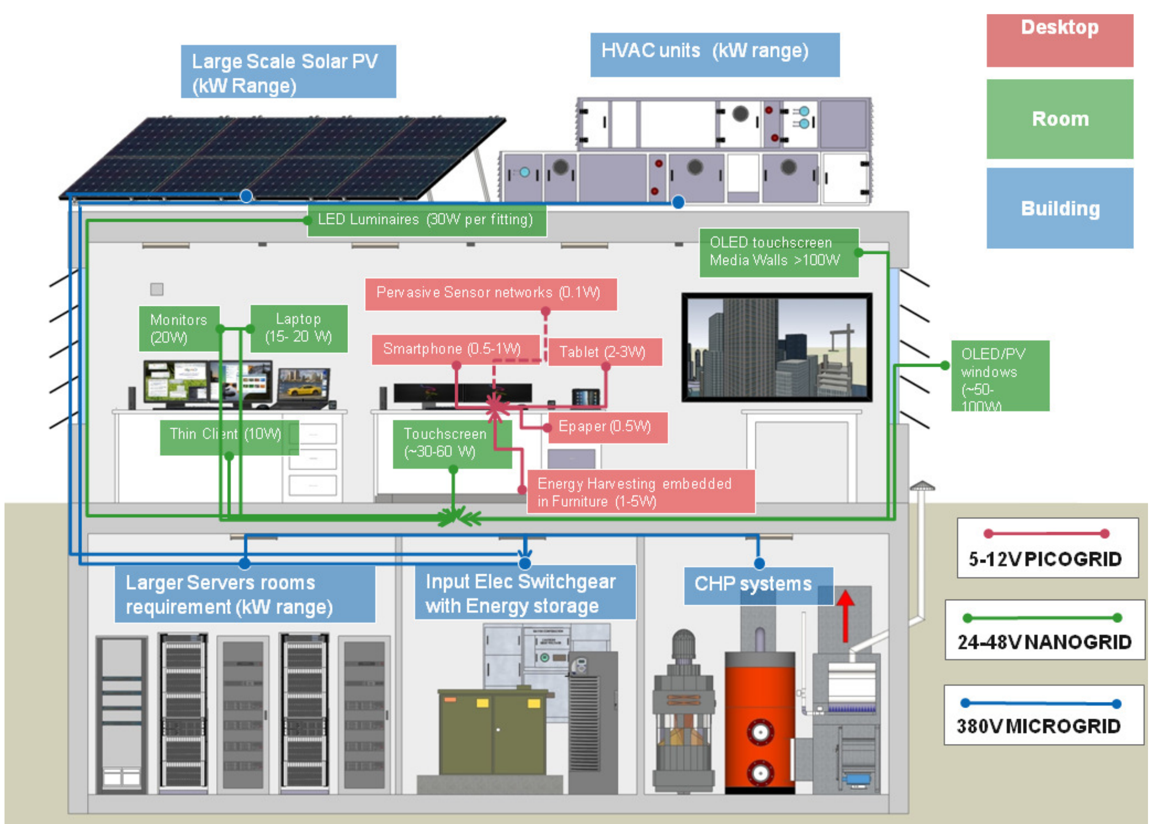


Figure 15: DENs Model for DC Microgrids in Buildings

5.2 Conclusion

The legacy ac power network in buildings today is optimized for a power system context over 100 years old. With the two major drivers of change, digital technology and distributed generation making a significant impact in office buildings today; a critical point is being reached where a complete rethink is now realistic.

Unlike the centralised ac network, where every socket is synchronised to an analogue nationwide grid, the new system should be asynchronous (dc), digitally controlled and actively use distributed energy assets instead of relying on a uni-directional power flow philosophy. Taking some guidance from Power over Ethernet, it is clear that developing a solution which is optimized for use (safety-extra-low-voltage in occupied zones) brings many cost and efficiency benefits.

Looking to the future, it appears that a number of different dc microgrid solutions will emerge, each optimized for a particular application or end-user in mind. Already there appears to be divergence between PoE-like solutions where power is sent down dedicated lines, and DC FlexZone Grid-like solutions where power is sent down shared conductors. Learning from the progress of the internet, this type of competition should be actively encouraged, as long as there is a superseding framework in place which can direct communication and interoperability between layers, and hence allow higher level applications (such as demand-side management controls) to be developed independently.

In this paper, a physical layer classification system for the Digital Energy Network (DEN) model was proposed: the microgrid: the building-wide network, the nanogrid: the room-wide network, and the picogrid: the desktop/appliance-wide network. Each layer should be optimized for its intended use; i.e. the room and desktop networks should be designed for high interaction with humans, rather than blindly optimized for a centralised national grid.

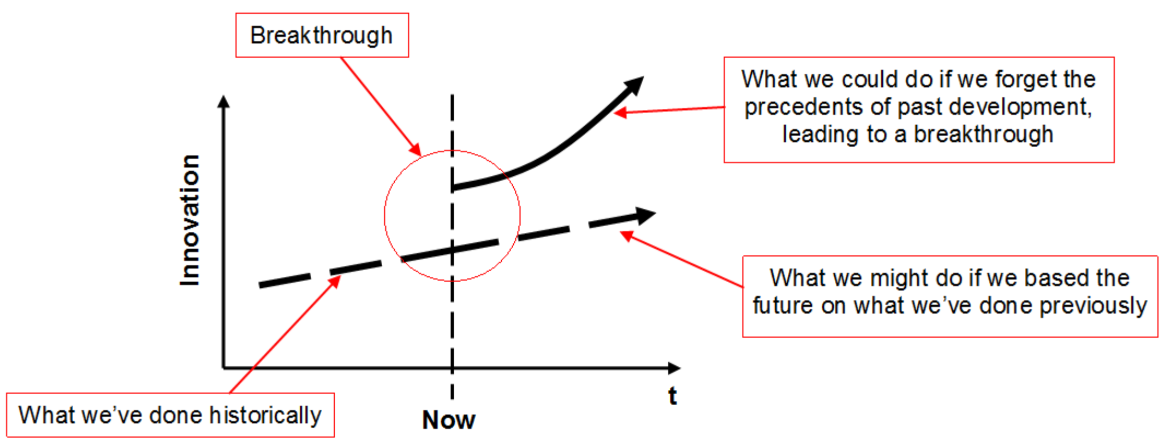


Figure 16: DC Buildings: Opportunity for Innovation

In summary, the electricity industry is possibly at a tipping point, and if it is willing to think outside the box; it could open up the opportunity for a breakthrough in the way power is delivered around buildings (see **Figure 16**). Using the DEN philosophy of distributed energy and occupant-centric design will bring further opportunities to increase efficiency and ultimately reduce costs and carbon impact.

Paper Acknowledgements
This paper contributes to a joint research project by Arup and BRE Trust at the University of Strathclyde. Special thanks go to Mike Gilmore, Mani Manivannan, Mike Summers, Matt Collinson, John Moss and David Deighton for checking the work.

References

1. Boyle G, Renewable Electricity and the Grid: The Challenge of Variability, Earthscan 2007, ISBN-13: 978-1-84407-418-1, pg 12
2. IET Wiring Regulations, (BS 7671:2008)
3. Bellis M, Patent List – Thomas Edison, About.com, online article, available here: http://inventors.about.com/library/inventors/bledisonpatents.htm (last accessed Dec 2011)
4. Ali@gwc.org.uk, Creative Commons Photograph, available here: http://en.wikipedia.org/wiki/File:Circuitbreaker.jpg (last accessed Dec 2011)
5. Hughes T P, *Networks of power: electrification in Western society, 1880-1930*, Johns Hopkins University Press,Baltimore 1983 ISBN 0-8018-2873-2 pg. 193
6. Morton A, *Managed DC Power Reticulation Systems*, University of Melbourne, 1999
7. Johnston J, Counsell J and Strachan P, *'Trends in Office Internal Gains and the impact on Space Heating and Cooling Demands'* CIBSE Technical Symposium, De Montefort University, Leicester, 6th and 7th Sept 2011.
8. CNET online Monitor comparison chart http://reviews.cnet.com/green-tech/monitor-comparison-chart/?tag=contentMain;contentAux (last accessed June 2011)
9. Koomey J, Berad S, Sanchez M, Wong H, Assessing trends in Electrical Efficiency of Computation over Time, IEEE Annals of the History of Computing, Aug 2009, IEEE
10. Gorrie W, DC Power Distribution in an Office Building, MSc Thesis, University of Manchester, 2005
11. Sannino A, Postiglione G, Feasibility of a DC Network for Commercial Facilities, IEEE Transactions on Industry Applications, Vol 39, No. 5, Sept 2003
12. Dekenah M, Power Quality – Ebook, 2004, published online: http://www.marcspages.co.uk/pq/3333.htm (last accessed Dec 2011)
13. International Energy Agency, Distributed Generation in Liberalised Electricity Markets, OECD/IEA, 2002
14. U.S. Department of Energy, Future Fuel Cells R&D, Online article: http://www.fossil.energy.gov/programs/powersystems/fuelcells/, last accessed Dec 2011
15. Park K, Kang G, Kim H, Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module, Energy 35 (2010) 2681–2687
16. European Photovoltaics Industry Association, Solar Photovoltaics: Competing in the energy sector, 2011, available: (http://www.epia.org/index.php?id=18)
17. Sills B, Solar May Produce Most of World's Power by 2060, IEA Says, online article, http://www.bloomberg.com/news/print/2011-08-29/solar-may-produce-most-of-world-s-power-by-2060-iea-says.html (last accessed Dec 2011)
18. Messenger R, Ventre J, Photovoltaics Systems Engineering, 3rd Ed.
19. Hammerstrom D, AC Versus DC Distribution Systems—Did We Get it Right? IEEE invited Paper, 2007
20. Metcalfe B, *Memo: Ether Acquisition*, A confidential fax memo, 1973, Xerox, Palo Alto http://ethernethistory.typepad.com/papers/ethernetbobmemo.pdf (last accessed Nov 2011)

21. IEEE Std 802.3af:2003
22. IEEE Std 802.3at:2009
23. Cisco, UPOE Powered Personal TelePresence Systems: Free the Power of your network, online article, available here: http://www.cisco.com/en/US/prod/collateral/switches/ps5718/ps4324/solution_overview_c22-676342.pdf (last accessed Dec 2011)
24. Mayell R, Simple Circuit Design Tutorial for PoE Applications, Online Article, http://www.eetimes.com/design/power-management-design/4012066/Simple-circuit-design-tutorial-for-PoE-applications?pageNumber=0 2006, (last accessed Dec 2011)
25. Gilmore M, Manivannan M, Telecommunications Cabling: Guidance on standards and best practice for construction projects, British Standards Institution 2012, ISBN 978-0-580-75607-8
26. Huntington J, Control Systems for Live Entertainment, 3rd Ed, Focal Press, 2007, ISBN: 978-0-240-80937-3, pg 40
27. Skinnybytes, Case Study: Purdue University, online article: http://skinnybytes.com/uploads/CaseStudy_Purdue_University.pdf (last accessed Dec 2011)
28. Armstrong, DC FlexZone Grid, Online article: http://www.armstrong.com/commceilingsna/article55189.html (last accessed Dec 2011)
29. Armstrong, DC FlexZone Grid: Electrical Design Guide, online article: http://www.armstrong.com/common/c2002/content/files/66701.pdf (last accessed Dec 2011)
30. Redwood Systems, Solutions, Online article: http://redwoodsystems.com/solutions (last accessed Dec 2011)
31. Symanski D, 380Vdc Data Center At Duke Energy, Emerging Technology Summit, Nov 9 2010, Sacramento, available online: http://www.emergealliance.org/imwp/download.asp?ContentID=19271 (last accessed Dec 2011)
32. Rasmussen N, AC vs DC Power Distribution for Data Centers, APC/Schneider Electric, Online white paper, http://www.apcmedia.com/salestools/SADE-5TNRLG_R6_EN.pdf (last accessed Dec 2011)
33. EMerge Alliance Members list: online publication: (last accessed Dec 2011) http://www.emergealliance.org/About/OurMembers.aspx
34. Patterson B, Symanski D, DC Distribution: The Power to Change Buildings, EMerge Alliance Presentation, available online (last accessed Dec 2011) http://www.emergealliance.org/imwp/download.asp?ContentID=20624
35. Palm E, "Enernet" – a smart-grid vision from a Net tycoon, CNET, 2009, available online: http://news.cnet.com/8301-11128_3-10203683-54.html
36. Metcalfe B, The Enernet, Presentation to Singularity University, July 2009, available online: (last accessed Dec 2011) http://www.youtube.com/watch?v=cA811EPzwLI&feature=player_embedded#
37. Metcalfe B, Toward Terabit Ethernet, OFC/NFOEC, Feb 2009, available online: http://www.youtube.com/user/OFCNFOEC#p/u/55/nKx12tCejO4
38. User:Kbrose, Creative Commons, available here: (last accessed Dec 2011) http://en.wikipedia.org/wiki/File:IP_stack_connections.svg
39. Wheeler D, The Most Important Software Innovations, Online article, Rev July 2011, http://www.dwheeler.com/innovation/innovation.html
40. PowerMat, Wireless Charging Manufacturer: http://www.powermat.com/ (last accessed Dec 2011)